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Post-consumer flexible polyolefine (FPO) as a material for bespoke 3D printing facades

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ABSTRACT: The paper explore the possibility of recycling post-consumer polymers from the Building & Construction industry (B&C), using Large Scale Robotic 3D Printing (LSR3DP) to produce bespoke building facade components. A case study is developed, in which a stock of Flexible Polyolefine (FPO) - resulting from the recycling of a roof waterproofing membrane - is transformed into a set of highly crafted façade/roofing shingles. The paper describes: 1) the material recycling process, 2) the material testing for LSR3DP, and 3) the fabrication of a 1:1 demonstrator.

1 INTRODUCTION

The Building and Construction (B&C) sector represents the second-largest application area for plastic materials, with consumption expected to grow from 64 million tonnes in 2020 to 97 million tonnes by 2040 (*OECD - 2024*). Within this sector, plastic applications range from siding (cladding), roofing, decking, piping, thermal insulation, and electrical insulation (Agarwal and Gupta, 2011). Traditionally, building components made out of plastic are produced using techniques such as extrusion and molding. However, similarly to what is happening in other fields, novel fabrication methods are emerging, allowing for a higher degree of flexibility. 3D printing, in particular, allows producing customized components at no extra cost, overcoming the economy of scale. (Tay *et al.*, 2017). In B&C, this technology has been boosted by the recent introduction of Large Scale Robotic 3D Printing (LSR3DP), which allows larger objects to be produced more quickly (Al Jassmi, Al Najjar and Mourad, 2018).

When discussing plastics, it is essential to highlight some criticalities related to their lifecycle. In particular, 1) most of the plastic produced today (99.5%) derives from fossil fuels (*EUBP Market Data Report - 2023*), (Storz and Vorlop, 2013), 2) plastic production accounts for a significant percentage of global greenhouse gas emissions (3.4% in 2019) (*Building Materials and the Climate - 2023*), and 3) worldwide, only a small percentage of End of Life (EoL) plastic is recycled (15%), the rest s burned or landfilled or lost in the environment (OECD, 2022).

These numbers highlight the urgent need to reduce the environmental harms of plastic usage, which on a practical level means increasing its recycling rate. Most plastics in use today are thermoplastics, which are easy to recycle as they become pliable and moldable when heated, and solidify upon cooling. Recycling plastic can save unrenewable resources, as it directly replaces virgin feedstock. In the same way, it can limit greenhouse gas emissions, as most plastic production-related emissions (61%) correspond to the initial resin production (*Zheng and Suh - 2019*).

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The present work aims to explore the possibility of using post-consumer plastic from B&C for LSR3DP applications, as limited studies exist in this field. Given the heterogeneity of thermoplastic used in B&C, a case study is created in which a stock of post-consumer waterproofing membranes is recycled and transformed into highly custom components for roofing/ facade applications.

2 METHOD

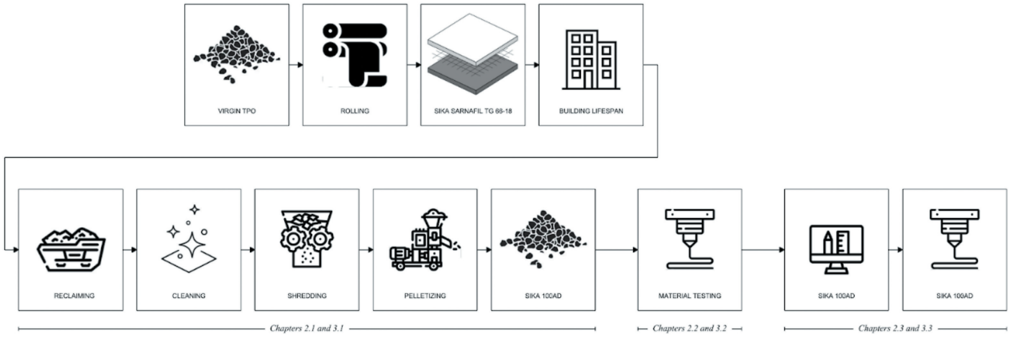

Figure 1. Method diagram.

2.1 *Material reclaiming and recycling*

The reclaiming and recycling of thermoplastic material is conducted in collaboration with the company SIKA (*Sika*, 2024). As part of an Extended Producer Responsibility (EPR) experimental program, SIKA had the possibility to withdraw a stock of post-consumer waterproofing membrane from a building on which a renovation had been scheduled. The building features a flat, roof, waterproofed with SIKA Sarnafil TG 66-18 (*Sarnafil-Tg-66-18 - 2024*).

SIKA Sarnafil TG 66-18 is a multi-layer synthetic roof waterproofing sheet made of two flexible polyolefin (FPO) layers reinforced by a non-woven interlayer of glass fiber which provides dimensional stability. FPO is a flexible thermoplastic, particularly suitable for outdoor applications due to its resistance to permanent UV irradiation. This material characteristic makes the product ideal for both ballast roofs (e.g. gravel, concrete slabs, green roofs) and exposed flat roofs. The recycling process involves multiple steps. First, the product needs to be detached from the roof. Second, both the upper and lower surface of the membrane need to be cleaned. Third, the material needs to be shredded into smaller particles. Fourth, the material needs to be processed into pellets suitable for 3D printing.

2.2 *Material testing for LSR3DP*

After recycling, the material is subjected to a preliminary testing phase. This phase aims to define the optimal set-up parameters for FPO extrusion, assess FPO's printability, and evaluate the qualities of the resulting 3D-printed object. This test is conducted using the 3D printing setup of ETH Zürich Robotic Fabrication Lab (RFL), which consists of a CEAD thermoplastic extruder (*CEAD - 2024)* attached to an ABB 4600 robotic arm, in turn, attached to a gantry system. The CEAD extruder needs to be fed with thermoplastic in the form of pellets. The extruder features four customizable heating zones for temperature control and a custom-made cooling device that releases compressed air of 0.6 bar pressure. The extrusion nozzle can be exchanged to adapt to the required extrusion width. The printing base consists of an 1180 mm by 380 mm MDF board of 18mm thickness backed on a heating mat, which can reach a surface temperature of about 60°C. The robotic toolpath is defined in the parametric CAD environment Rhinoceros + Grasshopper. The communication between the software and the robot is done using the framework COMPAS RRC (*COMPAS RRC* - 2024).

2.3 *Design and fabrication of the 1:1 demonstrator*

After testing whether reclaimed FPO can be used for LSR3DP applications, the experiment continues with the design and fabrication of a 1:1 demonstrator. This module aims to provide an example of how the material could be valorized using digital design and fabrication. One of FPO's main features is the capacity to withstand extended exposure to weather and UV light, a property that makes it suitable for outdoor applications. For this reason, the recycled material is given a new life within a custom facade/roofing system, specifically designed in the framework of the experiment. The system consists of discrete elements (shingles) attached to a timber substructure. In order to stress the design possibilities offered by the technology, the demonstrator features an organic, doubly curved geometry. All design operations are performed using the parametric CAD environment Rhino + Grasshopper. The fabrication setup used in this phase is the same as in the material testing phase.

3 RESULTS

3.1 *Material reclaiming and recycling*

The building from which the material was reclaimed is situated in Switzerland. Its roof consisted of a gravel-ballasted roof, waterproofed with SIKA Sarnafil TG 66-18. The building was scheduled for a general renovation which implies the addition of a new floor. In this framework, the membrane needed to be removed and disposed of, even though, having been installed for only 15 years, it had not reached its end of life from the serviceability perspective. As part of an EPR experiment, SIKA organizes the post-consumer withdrawal of the membrane. The withdrawal was performed by a specialized roofing contractor. During its lifecycle, the membrane had not been exposed to direct sun (UV rays) and weather, being protected by a separate covering and a layer of gravel. For this reason, upon reclaim, the material was found in good technical condition. After being exposed, the membrane was cleaned from coarse-soiling. Sarnafil TG 66-18 is a loose-laid waterproofing system, meaning it is not mechanically or chemically attached to the roof surface. This property represented a great advantage for the reclaim operation. The membrane was cut into pieces approx. 1.5 m wide and several meters long. These pieces were then rolled up, lifted from the roof with a crane, and finally stowed in pallets with wooden frames. Transportation was organized by a waste disposal service provider. In total, 9 tons of the product were reclaimed.

Figure 2. Different phases of the material reclaiming process: pre-cleaning, cutting, rolling, and storing.

After withdrawal, the membrane rolls were sent to a specialized recycling plant. Here, the material was cleaned, shredded, re-grinded, and finally extruded into a new compound. The material was re-compounded 1:1, without additives. Its final composition consists of FPO, with a minimal amount of glass fiber, as the membrane's reinforcement is not separated from the thermoplastic before shredding. The color is dark grey, as a result of the mixing of the membrane's upper white layer and black lower layer. The resulting recyclate can be integrated, in definite amounts, into the production of new membranes replacing virgin resin.

Figure 3. Different phases of the material recycling process: cleaning, shredding, and grinding.

3.2 *Material testing for LSR3DP*

Before testing for LSR3DP, the material was dried for 8 hours at 85°C in a VisMec Dryplus 50 dryer. A 4 mm nozzle was mounted on the extruder. A first experiment was held to find the set-up parameters for FPO extrusion. From the literature, it was acknowledged that FPO melting temperature ranges from 140°C to 260°C. The four CEAD extruder heating zones are generally set to values that progressively increase towards the nozzle with steps of about 10°C between one and the other. The temperatures were initially set to Z1=230°C, Z2=240°C, Z3=250°C, Z4=260°C, and the extrusion activated with the motor velocity set to 10 RPM. The robot was not moving, and the nozzle was placed at about 1 m in height from the printing base. During extrusion, the viscosity of the extruded material was observed. The temperatures in the extruder heating zones were gradually reduced to identify a balance between material viscosity and motor utilization. This condition was found in the following values: Z1=170°C, Z2=180°C, Z3=190°C, Z4=200°C.

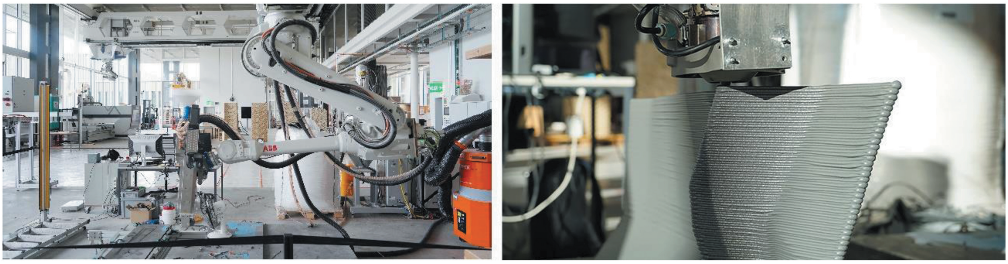

Figure 4. The LSR3DP setup at ETH Zürich; Initial material test.

A second operation was held to assess the material printability. A test geometry was defined, comparable to the one envisioned for the shingles of the final demonstrator (Chapter 2.3, Chapter 3.2.2). The layer height was set to 2mm. During printing, the velocity of the robot was progressively increased from 5 to 40 mm/s. The extruder integration automatically synchronizes the material flow with the robot speed (higher speed corresponding to more extrusion) so that the 3DP layer width remains consistent besides velocity changes. Even at higher RPM, the motor could handle the material extrusion without surpassing the torque and utilization thresholds. Given the relatively small scale of the test geometry, however, higher velocities correspond to printing failure as the deposited material does not have enough time to solidify before receiving the upcoming layer. The appropriate velocity for the print was therefore found at 30 mm/s. The printing base was heated up to 60°C. With this condition, the material presented a good adhesion to the base. The print could be completed without the need for a brim or mechanical connection of the part to the base. In general, FPO 3D printing proved to be a reliable process, characterized by no warping, no delamination, and no cracking. The resulting object presents a certain flexibility, which can be used, in the case of building components, to absorb tolerances during the assembly.

3.3 *Design and fabrication of the 1:1 demonstrator*

3.3.1.1 *Design of timber substructure*

The timber substructure comprises timber planks with a cross-section of 60mm x 60mm, arranged in two orthogonal directions. The vertical beams run continuously across the structure, while the horizontal ones are discontinuous, and act as connectors distributed at regular spacing. The vertical beams are rotated at a certain angle around the normal vector to allow space for screwing at both extremes, a concept borrowed from the Zollinger "Lamella roof" design. The demonstrator's final configuration features 5 vertical beams, separated by sets of four horizontal ones. Each vertical beam undergoes a geometric transformation relative to its neighbors, collectively forming a ruled surface. The resulting distorted grid consists of 12 unique, quadrilateral cells, with an average size of 520 x 680 mm. To each of these spaces corresponds a covering element ("shingle"), 3D printed out of recycled FPO.

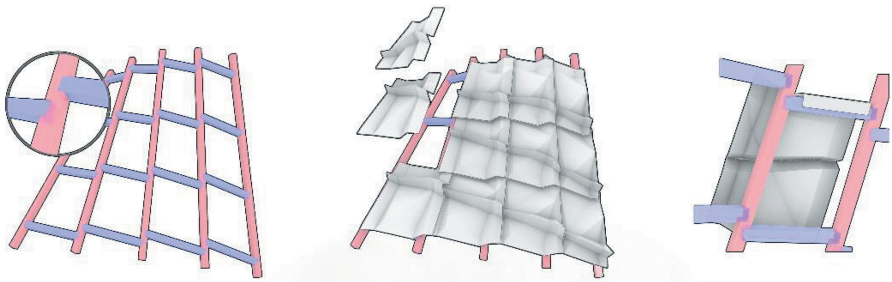

Figure 5. Timber substructure, Final demonstrator, Shingle assembly on timber frame.

3.3.2 *Design of the 3DP shingles*

A great advantage of 3D printing is the possibility to create complex geometries with no additional effort or cost. This advantage has been leveraged by embedding multiple functionalities directly into the geometry of the shingles, maximizing the material's potential within an integrated form. First, a fold has been created on the component's upper edge, allowing an integrated connection to the structure's horizontal components. Second, the component's lower and right edges have been shaped to guarantee a progressive overlap and prevent water infiltrations. Third, a diagonal crease has been added to absorb the local curvature. Fourth, a horizontal ridge has been introduced, to increase stiffness and stability during fabrication. The geometry of the shingles has been produced using algorithmic design tools. Although similar to each other, the components are all geometrically unique, adapting to the substructure's irregular geometry. During the design phase, not only the advantages of R3DP were taken into account, but also its limitations. This technology creates 3 dimensional objects depositing material in one layer on top of the other. For this reason, geometries characterized by overhangs or extreme inclinations cannot be produced as the new layer, in these points, would not find the appropriate support underneath. The shingle fabrication strategy implies reorienting the geometry with one of the sides on the XY printing base. The shingle position on the assembled structure is therefore rotated 90 degrees compared to the one during fabrication. From a design perspective, this implies, first, that the side used as a base needs to be planar and, second, that the shingle vertical section needs to avoid overhangs and steep inclinations.

3.3.3 *Fabrication of the timber substructure*

Given the complexity of the geometry, the timber planks were prefabricated using a CNC machine. The vertical beams were cut manually with a length of 2500 mm and then milled to produce connection pockets. The horizontal beams were pre-cut with a length of 1000 mm, and then CNC cut at a precise angle with a circular blade. The geometrical information from the 3D model was translated into a HOP file format that the machine could interpret using COMPAS

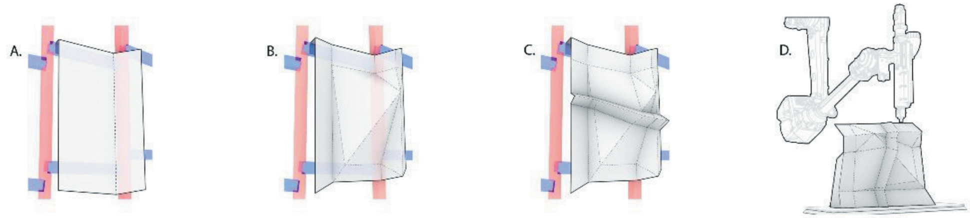

Figure 6. Orientation of the shingle on the 3D printing base.

TIMBER (*Gramazio Kohler Research*, 2024). During production, each component was tagged with a unique code to simplify the assembly process. To allow the structure to stand in an upright position, a diagonal support was added at the back. The assembly was performed by two people. Overall, the fabrication and assembly of the timber structure took about one working day.

3.3.4 *Fabrication of the 3DP shingles*

The fabrication of the covering elements began with computing the 3D printing toolpath for each individual shingle. Due to the object's geometrical complexity, this process could not be done simply by intersecting the 3D model with a set of horizontal planes (planar slicing) but required a rather more sophisticated non-planar slicing algorithm (Nayyeri, Zareinia and Bougherara, 2022). The resulting layers had variable heights and required the dynamic adjustment of the material flow during fabrication. This feature was integrated into the extruder control. The material flow was dynamically tuned to achieve a 10mm wall thickness. Since the horizontal cross-section of the shingle oriented on the printing base was not a closed polyline, the robot tool path could not be programmed as a continuous spiral movement. On the contrary, at each layer, the robot needed to change direction and move back on its way. Generally, this condition is not ideal, as the first part of the layer is deposited onto material that has only recently been placed, and therefore has not had sufficient time to solidify properly. The problem is more severe at the extremes of the print path and mitigates progressively towards the layer midpoint. To remedy this situation, the robot velocity was programmed to dynamically decelerate at the beginning and end of the layer (40mm/s to 5mm/s). This allowed for reducing imperfection at these points.

The 3D printing of the shingles varied between 3 and 5 hours, depending on the variable size. The resulting objects present a generally high printing quality, with some irregularities (e.g. over-extrusion, layer sinking), which does not compromise the component's functionality and could have been avoided with additional fine-tuning of the printing parameters (e.g. material flow and velocity). The final components feature a dark grey/opaque-black color and present a slightly reflective surface finish, which lends itself to interesting lighitng effects. The average weight of a shingles is 4.80kg. Overall, 57.7 kg of material was used.

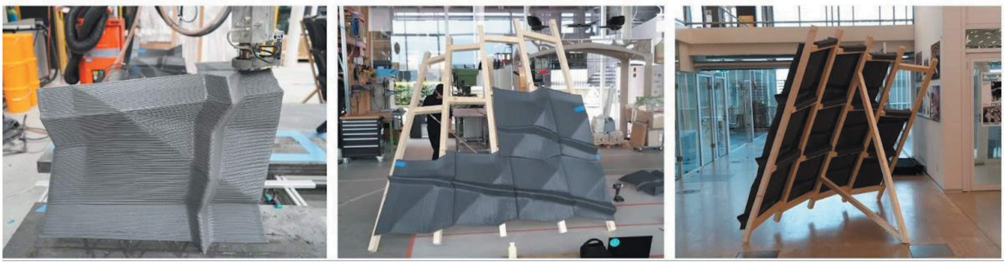

Figure 7. Final shingle, assembly, final mockup.

4 CONCLUSION

The present work describes an experiment in which post-consumer thermoplastics from the B&C industry are recycled and used to produce bespoke building components through LSR3DP. In particular, a stock of waterproofing membranes has been reclaimed, compounded, and transformed into a modular roofing/facade system. Value and functionality were retained during the transformation, as the material's second life as a facade material makes use of its UV and weather resistance. In its first lifecycle, the material took the form of a standard, generic product. In its second iteration, however, it transforms into a crafted, high-value, custom-designed building system.

From a technical perspective, the experiment demonstrates that no major challenge exists in using post-consumer FPO for LSR3DP applications. This statement is backed up by the observation of 1) a low warping tendency due to the material's natural flexibility and 2) no occurrence of delamination between the 3DP layers. The material can be printed at a relatively low temperature (200°C), a fact which opens up its use on a wide range of 3DP hardware. Finally, it presents a high degree of adhesion to the printing base and, therefore, does not require brims and mechanical connections.

From a conceptual perspective, the experiment highlights the fact that, when framed in a global recycling logic, thermoplastics have the potential to be considered a "liquid" asset. The form that the component assumes in one use cycle does not constrain the use of the material in the next cycle, as it can be easily reshaped, adapting to the new functionality. In this perspective, technologies such as LSR3DP, which can flexibly produce unique geometries, are particularly valuable.

Besides technical and conceptual conclusions on the material itself, the experiment highlights the importance of innovative B&C practices oriented to improve circularity. Often, the barrier to recycling lies not in a lack of appropriate technology but in the absence of systematic thinking about the building's lifecycle. For example, buildings are rarely designed for disassembly, components are not typically created with recyclability in mind, and materials are frequently mixed during demolition. To address these challenges, emerging innovations - such as "the Building as a material bank" (BAMB), (Rose & Stegemann, 2019), extended producer responsibility (EPR) (Leal Filho et al., 2019), the digital product passport (Adisorn et al., 2021), etc. - should be actively promoted, as they have significant potential to drive meaningful change. In the present case, the EPR program set up by SIKA was fundamental, as it facilitated a batch of clean, professionally recycled material.

5 OUTLOOK

Despite the positive results of the experiment, some questions remain open.

First, the post-consumer waterproofing membrane used in this experiment was in good technical condition. This is because, on one side, it had not yet reached the end of its service life, and on the other, it was protected during use by an additional membrane layer and a covering of gravel. Further research is necessary to determine whether membranes in poorer technical conditions could undergo similar recycling processes effectively or would rather require the addition of additives (e.g. a stabilizer) during re-compounding.

Second, in this experiment, only a single recycling cycle was completed. The material may have the potential to withstand multiple recycling cycles before reaching a state where it is no longer serviceable, though this durability will likely vary depending on the specific application. Future studies should aim to evaluate the material's resilience across multiple cycles of use and recycling to better understand its long-term viability.

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